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Assessing the economic value and structure of large-scale electricity storage

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Assessing the economic value and structure of large-scale electricity storage

Alan Lamont

Abstract

If large-scale electricity storage becomes a significant technology in the energy system, it will be large enough to affect the prices on the system. The changes in system prices will affect both the optimal economic penetration of storage itself, and the penetration of other technologies, including renewables. This research develops a theoretical framework to define the optimal operation of a storage system taking into account the effect on system prices, and to evaluate the marginal values of the charge and discharge power capacity and the energy storage capacity of a system. The theoretical approach is applied to a realistic system model to derive the marginal values of the charge and discharge power component and the energy storage component at various levels of penetration. The results illustrate the decline in marginal value of components, and the impact that the capacity of one component has on the marginal value of the other.

1. Introduction

It is frequently suggested that large-scale energy storage will be an important part of a future, low carbon energy system. Proposed future energy systems based on large renewables either explicitly or implicitly assume that there will be substantial storage available to make efficient use of the intermittent power generation through arbitrage between periods of high energy availability and periods when energy is scarce (Jacobson and Delucchi (2009), Hoffman, et al (2009), Turner (1999)). Storage could also be used to make more effective use of low-carbon baseload generation by storing electricity from baseload electricity overnight and releasing it during the day. To assess the viability and the role of large-scale electricity storage, it is necessary to identify and evaluate the factors that determine the economic penetration of storage, the optimal structure of a storage system, and the economic interaction between storage and generation technologies. This paper develops a theoretical, optimizing framework to assess the marginal value of a storage system and its components, and to determine how the system should optimally be operated. It then presents a practical example to illustrate the marginal values of charging and discharging capacity and storage capacity.

A number of studies have assessed the economic viability of electricity storage in different markets (Eyer et al, 2004), Iannucci et al, 2003), (NYSERDA, 2007), (Korpaas, et al, 2003), (Lamont, 2003), (EPRI, 2007). These studies considered small-scale storage—systems that are small enough that they do not affect operation or prices of the electric system as a whole. These evaluated the net revenues that would accrue to the owner of a storage facility and compared them to the cost of installing and operating the storage facility. Analysis of small-scale systems gives a good understanding of the possibilities for initial penetration of storage. These essentially tell us the cost point at which an investor might be willing to invest in the first storage facility in a given market. However, analysis of small-scale systems does not provide a basis for estimating eventual market penetration of large-scale storage nor the effect that storage might have on the balance of the system.

Large-scale storage affects the system by increasing the load on the system and raising prices when it charges, and decreasing the load and lowering prices when it discharges. By changing prices, storage can affect the economics and investments in the generators on the system. For example, it is often suggested that storage will enable the large-scale penetration of renewables such as wind. Large-scale wind will tend to depress prices in those hours that it generates the most. This reduces the marginal value of wind capacity and limits further investment (Lamont, 2008). However, the charging of storage in those hours would increase loads and prices and encourage further investment in wind.

As storage penetrates the system, the marginal value of capacity decreases since it raises the prices during charging hours and decreases the prices during discharging hours and decreases the net revene. Eventually further investment is not economic and there is no further penetration.

Assessing the role and penetration of large-scale storage requires understanding the way that storage will affect prices, and, in turn, the effect of prices on the economics of storage. The impact of storage on prices has been mentioned as an issue in some studies (e.g. NYSERDA, 2007). Sioshansi et al (2009) estimates the price impact of large-scale storage in order to evaluate the welfare implications of changing prices in the PJM system. However, these do not analyze the optimal operation of storage taking into account the effect of storage on prices, nor do they assess the impact of the changing prices on the economic viability of storage.

The overall economic effect of storage is determined by both the magnitude and duration of the price changes. The magnitude of the price change is determined by the charge and discharge power capacity since this determines the degree to which storage can change the loads on the system. The duration of price changes are determined by the energy storage capacity of the system. The analyses of small systems do not address the economics of charging capacity since, by definition, the charging capacity small enough that it does not affect prices on the system. However, charging and discharging capacity is a substantial part of the cost of a storage system (Johansson, et al, 1993) (Boutacoff, 1989), (ESA, 2009). The costs and marginal value of the charging/discharging capacity have a substantial effect on the design of the system.

In general, the charge/discharge power capacity can be sized separately from the energy storage capacity. As either type of capacity is increased, its marginal value decreases. In addition, changing the level of one type of capacity will change the marginal value of the other type. The practical illustration portion of this paper uses the optimality conditions from the theoretical analysis to compute the marginal values of charge/discharge capacity and storage capacity. From this information it develops a contour map of the marginal values of both types of capacity. This map shows the optimal levels of the capacities as a function of their costs.

This analysis uses an optimizing framework where charging and discharging decisions are made with perfect knowledge of future conditions. When storage is actually operated in the field, it must be operated with stochastic estimates of future conditions and will not be as efficiently operated as in the optimized model. However, the optimization model provides two essential understandings. First, it identifies the principles of optimal operation to maximize the value of the storage. In the stochastic context this tells us the parameters that should be estimated and the procedures for using them to operate the system. Second, the optimization model approach estimates the maximum value that storage can provide. This allows us to determine whether or not storage would be worthwhile in a given situation. Since storage can be configured with many different technologies with different efficiencies and different costs of the component parts, optimization model can suggest the best type of technology to use in a given situation and the benefits of research and development for different components of the system.

A large-scale storage system might develop through the installation of a few large, utility owned centralized installations, or through the aggregation of thousands of small-scale installations. Either case would have approximately the same impact on the system as a whole, provided that they are operated efficiently.

We note that storage might play a number of economically useful roles in a system aside from arbitrage. Among them are: regulation, congestion relief, and transmission deferral (Eyer et al, 2004). These applications require different forms of analysis than what is presented here. This analysis only addresses arbitrage in large-scale systems.

2. Analytic model of large-scale storage

The analysis used here develops a cost minimizing optimization model of the system to clarify how the system should be optimally structured and operated. To state the problem: Let us assume that there is a set of generators meeting the demands over a year's operation. For convenience we will break the year into one hour periods (8,760 hours for the year), although the analysis could be conducted at any other period length. At each hour the end-use demand is met by dispatching the generators and, possibly, the storage. The generators can be a mixture of dispatchable and intermittent generators. The storage system can charge from the generators. Given the set of hourly demands, costs and efficiencies of the generators, and the hourly production of the intermittent generators, the model determines the condition for the cost minimizing configuration and operation of all the generators and the storage system. This is essentially an extension of the optimal capacity expansion model with intermittent generation presented in Lamont (2008).

Figure 1 illustrates the three basic components of the storage system: The storage reservoir--this might be a literal reservoir in the case of pumped hydro storage, a chemical compound, a tank of hydrogen, or a spinning flywheel--and the charge and discharge devices. In the case of electro-chemical storage this is basically wiring, although it might include structures for heat dissipation. In the case of pumped hydro, it is a pump-generator. For compressed air energy storage, it is a compressor (usually part of a combustion turbine). For most storage systems the same physical device charges and discharges the reservoir, although logically these can be separate devices. The mathematical analysis treats them as separate devices. However, it is easy to deal with the case where they are the same device.

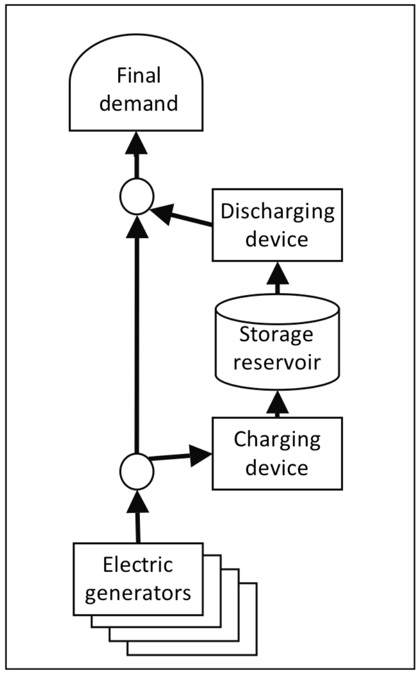

Figure 1: schematic of energy storage in the generation system

2.1. Nomenclature

The generation technologies are denoted by the subscript a. These are dispatched to meet the demand in each hour, D_h. Some of these technologies are intermittent so that in some hours their *available* capacity is only a fraction, $F_{a,h}^{prd}$, of their nameplate (or peak) capacity. For a dispatchable generator, $F_{a,h}^{prd}$ is 1.0 for each hour (we ignore forced outages in this analysis). Each generator will be dispatched to its full *available* capacity for at least one hour in a year[1].

The storage goes through a number of cycles of completely charging and discharging. The energy stored might increase and decrease during a cycle, but the cycle is only complete once the storage has completely charged and then completely discharged. Figure 2 illustrates the charging and discharging and shows the variables used to characterize the cycling of the storage. We identify the cycles by the subscript j. Here it is assumed that the storage starts off empty at hour e_j. It then charges until completely full by hour f_j. To complete the cycle, it completely discharges by hour e_{j+1}.

The hours at which storage completely charges and completely discharges are decision variables in the problem. The formulation below initially treats these are given.

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[1] If it is not dispatched to full capacity at least once, then it has more capacity than is optimal.

That is, the optimal charging and discharging each hour and the marginal values of capacity are computed given these hours. A separate computation is needed to find an efficient set of values for e_j. and f_j. The approach used here is discussed in the practical illustration portion of the paper.

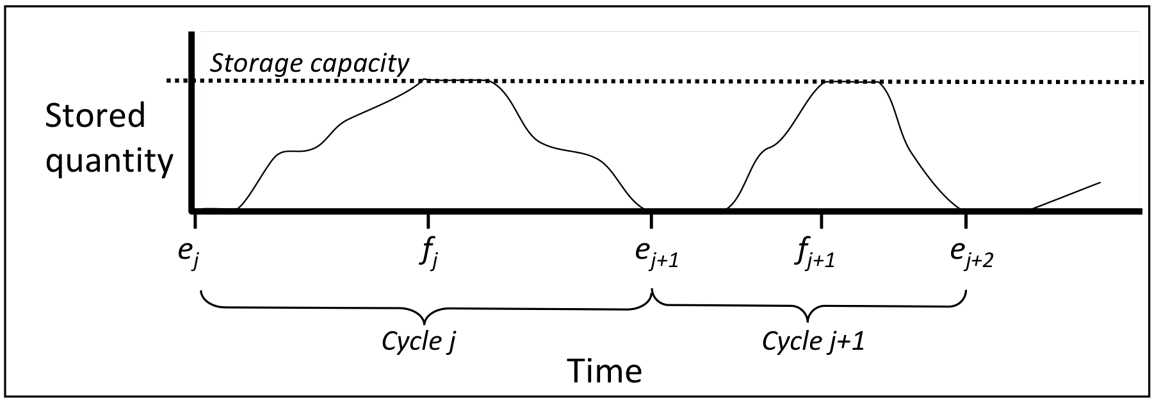

Figure 2: Illustration of the nomenclature for charging and discharging cycles

The formulation below is a constrained optimization. A number of the constraints require that the dispatch of a device (a generator or the charge and discharge devices of the storage) in each hour must be less than or equal to its capacity. To simplify the equations, we only represent those hours when the device is dispatched to its full capacity and the constraint is binding—the other hours have no effect on the analysis. We denote the set of hours that generator a is dispatched to its available capacity as H_a^*.

The full set of variables and parameters is as follows:

Subscripts and superscripts:

a	=	designates generators, when appropriate this includes storage charge and discharge devices
c	=	designates the charging device for storage in those cases where it is clearer to distinguish them from the generators
d	=	designates the discharging device for storage in those cases where it is clearer to distinguish them from the generators
r	=	designates the storage reservoir
h	=	designates an hour of the year
j	=	designates a charge/discharge cycle
cap	=	designates annual capacity costs
var	=	designates variable costs

Objective function:

C^{tot} = total annual cost of system, \$/yr

Decision variables:

k_a = the capacity of generator *a*, which is the peak output available from generator *a*, kW. This includes the capacity of the storage charging and discharging devices.

k_r = capacity of the storage reservoir, kWh

$g_{a,h}$ = output, or dispatch, of generator *a* in the hour h, kW.

f_j = the hour that the storage reservoir fully charges on cycle *j*

e_j = the hour that cycle *j* begins, with storage level at 0

Model parameters:

C_a^{cap} = annual capital cost of one unit of capacity for generator *a* or for the charge and discharge devices, \$/kW-yr

C_r^{cap} = annual capital cost for one unit of reservoir capacity, \$/kW-yr

C_a^{var} = variable operating cost of generator *a*, including the charge and discharge devices, \$/kWh

D_h = demand in hour *h*, kW

η_d = efficiency of the discharge device

η_c = efficiency of the charge device

$F_{a,h}^{prd}$ = production factor for generator *a* in period *h*. This is the fraction of peak output that generator *a* can provide in period *h*. If $F_{a,h}^{prd}$ = 1.0, the available output of the generator equals its peak capacity. If $F_{a,h}^{prd}$= 0.5, the available output is 0.5 of its peak capacity. For a dispatchable generator $F_{a,h}^{prd}$=1 in all hours.

Sets and references to elements of sets

H_a^* = the set of hours where generator *a* is dispatched to its full available capacity.

H = all hours in a year.

J = indices of all charging/discharging cycles.

$j(h)$ = the fill/empty cycle that contains hour *h*

2.2. Analytic model

The model minimizes the total annual cost of the system, which is the sum of the annualized capital costs for all the generators plus their operating costs over the year.

The minimization is subject to the constraints that the total output each hour must equal the demand that hour, the dispatch of each generator must be less than or equal to its available capacity, and the storage must complete each cycle by fully charging and discharging.

Objective: Minimize total annual cost

$$C^{tot} = \sum_{a} C_a^{cap} \bullet k_a + \sum_{h} \sum_{a} \left(C_a^{\mathrm{var}} \bullet g_{a,h} \right) + C_r^{cap} \bullet k_r \qquad 1$$

Subject to the following constraints:

Cannot exceed capacity of any generator or charging device (this formulation uses an equality constraint for those hours that the capacity constraint is binding)

$$g_{a,h} = F_{a,h}^{prd} \bullet k_a \qquad \forall a,\ h \in H_a^* \qquad 2$$

Meet the demand in all hours, including the charging demand

$$\sum_{\mathrm{a} \neq \mathrm{c}} g_{a,h} = D_h + \frac{g_{c,h}}{\eta_{\mathrm{c}}} \qquad \forall\ h \in H \qquad 3$$

Storage must charge to capacity each cycle:

$$\sum_{\mathrm{i}=\mathrm{e}_{\mathrm{j}}}^{\mathrm{f}_{\mathrm{j}}} \left(g_{c,i} - \frac{g_{d,i}}{\eta_d} \right) = k_r \qquad \forall\, j \in J \qquad 4$$

Storage reservoir must discharge to zero each cycle

$$\sum_{\mathrm{i}=\mathrm{f}_{\mathrm{j}}}^{\mathrm{e}_{\mathrm{j+1}}} \left(\frac{g_{d,i}}{\eta_d} - g_{c,i} \right) = k_r \qquad \forall\, j \in J \qquad \mathbf{5}$$

The complete Lagrangian is:

$$
\begin{aligned}
L = & \sum_a k_a \bullet C_a^{cap} + \sum_h \sum_a C_a^{\text{var}} \bullet g_{a,h} + k_r \bullet C_r^{cap} \\
& + \sum_a \sum_{h \in H_a^*} \gamma_{a,h} \left(g_{a,h} - F_{a,h}^{prd} \bullet k_a \right) && \text{do not exceed capacities} \\
& + \sum_h \lambda_h \left(D_h + \frac{g_{c,h}}{\eta_{\text{c}}} - \sum_{\text{a} \neq \text{c}} g_{a,h} \right) && \text{meet demand} \qquad 6 \\
& + \sum_j \alpha_j \left(k_r - \sum_{\text{i}=\text{e}_\text{j}}^{\text{f}_\text{j}} \left(g_{c,i} - \frac{g_{d,i}}{\eta_d} \right) \right) && \text{storage charges to capacity} \\
& + \sum_j \beta_j \left(\sum_{\text{i}=\text{f}_\text{j}}^{\text{e}_{\text{j}+1}} \left(\frac{g_{d,i}}{\eta_d} - g_{c,i} \right) - k_r \right) && \text{storage discharges to zero}
\end{aligned}
$$

2.3. The derivatives of the Lagrangian and their interpretations

The sections below find the derivatives with respect to each of the variables in the Lagrangian. The resulting equations have interpretations for the optimal operation of the system and for the computation of the marginal values of the components of the system.

In these interpretations, the Lagrange multipliers play a prominent role. To clarify the following discussion, the interpretation of the multipliers is discussed below:

- λ_h is the Lagrange multiplier for the constraint that the sum of the output from the generators plus the discharge of the storage must equal the demand in hour *h*. λ_h is the system marginal cost (SMC) in hour *h*. It is the reduction in cost that would result from reducing the demand by one unit. It equals the marginal generating cost of the most expensive generator that has been dispatched.
- $\gamma_{a,h}$ is the multiplier for the constraint that the dispatch of generator *a* cannot exceed the capacity of generator *a*. It is the reduction in cost that would result from increasing the capacity of generator *a* by one unit in hour *h*.
- α_j is the multiplier for the constraint that the storage must completely charge in cycle *j*. It is the marginal system cost of adding a more unit of energy to storage in cycle *j*.
- β_j is the multiplier for the constraint that the storage cannot discharge below zero during cycle *j*. It is the marginal system savings that would result if there were one more unit of energy in storage. This is the same as the marginal revenue to the storage device of releasing an additional unit of energy from the storage reservoir.

In the discussion below the variables α_j, β_j, f_j, and e_j must be determined to optimize the operation. However, the equations do not provide an explicit method for determining their values. In an optimization model these can be determined through an algorithm. In the operation of a real system the operators will estimate them based on forecasts of future conditions.

The values of f_j, and e_j are decision variables. However, in the formulation below they are treated as given and the other values are optimized given their values. An approach to determining these values is discussed in the example analysis.

The first constraint in the Lagrangian specifies that a generator cannot be dispatched greater than its capacity. In many hours of the year this will not be a binding constraint for a given generator (including the charge and discharge devices for the storage). Consequently, in the discussions below the derivatives for hours when this is a binding constraint ($h \in H_a^*$) are presented separately from the derivatives for hours when it is not binding

The next sections present the derivatives of the Lagrangian with respect to each of the variables in the analysis and interpret them in terms of the operation of the system and the marginal values of capacity of the components.

Derivative wrt the dispatch of the generators, $g_{a,h}$: Dispatch and marginal value of generation capacity

This provides the conditions for optimal operation of the generators capacities. Note that the storage charging and discharging devices are not included here since their conditions are somewhat different.

$$\frac{\partial L}{\partial g_{a,h}} = \begin{cases} C_a^{\text{var}} - \lambda_h & h \notin H_a^*,\ a \neq c,d \\ C_a^{\text{var}} + \gamma_{a,h} - \lambda_h & h \in H_a^*,\ a \neq c,d \end{cases}$$

Setting to zero and re-arranging we obtain

$$\lambda_h = C_a^{\text{var}} \qquad h \notin H_a^*,\ a \neq c,d \qquad \text{7a}$$

$$\gamma_{a,h} = \lambda_h - C_a^{\text{var}} \qquad h \in H_a^*,\ a \neq c,d \qquad \text{7b}$$

The condition in equation 7a applies when generator *a* is not dispatched to its full available output in hour *h*. The generator should be dispatched such that its marginal operating cost is equal to λ_h, the marginal system cost in that hour. The variable costs in this formulation are constant so a generator is dispatched if its variable cost is less than or equal to λ_h , and is not dispatched otherwise. The fact that the variable costs are constant is not crucial in this formulation. If variable costs changed as a function of output, the generator would be dispatched up to the level that its variable cost equals the system marginal cost.

In the second condition, 7b, the generator is dispatched to its full capacity. The system marginal cost will be greater than, or equal to, the generator's marginal operating cost. The difference between the generator's marginal operating costs and the system marginal cost is $\gamma_{a,h}$. This is the value that an additional unit of capacity would provide in that hour, provided it generates at full capacity. Intermittent generators often generate at less than full capacity, so this value must be modified to account for the reduced capacity. This is discussed below.

Derivative wrt the rate of charge, $g_{c,h}$: Dispatch and capital recovery of the storage charging device

This derivative provides the conditions for the optimal dispatch of the charging device. These conditions indicate the level of dispatch of the charging device and the contribution to the marginal value of the charging capacity in hour *h*. There are four different conditions that give us four different derivatives depending on whether the charging device is dispatched to capacity (so that the constraint is binding) and whether the system is in the charging or discharging interval of a cycle.

$$\frac{\partial L}{\partial g_{c,h}} = \begin{cases} \text{charging interval}, \quad j(h) \begin{cases} C_c^{\text{var}} + \dfrac{\lambda_h}{\eta_c} - \alpha_{j(h)} & h \notin H_c^* \\ C_c^{\text{var}} + \gamma_{c,h} + \dfrac{\lambda_h}{\eta_c} - \alpha_{j(h)} & h \in H_c^* \end{cases} \\ \text{discharging interval}, \quad j(h) \begin{cases} C_c^{\text{var}} + \dfrac{\lambda_h}{\eta_c} - \beta_{j(h)} & h \notin H_c^* \\ C_c^{\text{var}} + \gamma_{c,h} + \dfrac{\lambda_h}{\eta_c} - \beta_{j(h)} & h \in H_c^* \end{cases} \end{cases}$$

Setting the derivatives in the equations above to zero and re-arranging we obtain the following set of conditions to met in hour *h*:

$$\begin{array}{ll} \text{charging interval}, \quad j(h) \begin{cases} \lambda_h = \eta_c\left(\alpha_{j(h)} - C_c^{\text{var}}\right) & h \notin H_c^* \qquad \text{8a} \\ \gamma_{c,h} = \alpha_{j(h)} - \left(C_c^{\text{var}} + \dfrac{\lambda_h}{\eta_c}\right) & h \in H_c^* \qquad \text{8b} \end{cases} \\ \text{discharging interval}, \quad j(h) \begin{cases} \lambda_h = \eta_c\left(\beta_{j(h)} - C_c^{\text{var}}\right) & h \notin H_c^* \qquad \text{8c} \\ \gamma_{c,h} = \beta_{j(h)} - \left(C_c^{\text{var}} + \dfrac{\lambda_h}{\eta_c}\right) & h \in H_c^* \qquad \text{8d} \end{cases} \end{array}$$

To interpret these equations we note that when the system marginal price is very high, the storage does not charge at all. When the SMC is low, the storage charges at the full capacity of the charging device. At intermediate SMCs the storage charges at a rate that is less than the full capacity of the charging device.

Figure 3 illustrates the behavior of SMCs during a charging interval. At the start of the interval the end-use demands on the system are relatively high so the SMC is high, as indicated by the fine line in the figure. The SMC decreases as the end-use demands decrease. At hour **a** the SMC declines to $\lambda_h = \eta_c\left(\alpha_{j(h)} - C_c^{\text{var}}\right)$ and the storage begins to charge. As it charges it adds load on the system, holding the SMC constant, following the heavy line in the figure. Between hours **a** and **b**, it places enough additional load on the system to maintain the SMC at $\eta_c\left(\alpha_{j(h)} - C_c^{\text{var}}\right)$ as required by equation 8a.

The hours between **a** and **b** are marginal hours for charging during this cycle. $\alpha_{j(h)}$ is the marginal cost of adding energy to the storage reservoir. Rearranging Equation 8a shows the marginal cost of adding a unit of energy to storage during this interval incurs a unit of variable operating cost plus the system marginal cost divided by the efficiency of the charging device:

$$\alpha_{j(h)} = C_c^{\text{var}} + \lambda_h / \eta_c$$

At hour **b** the end-use demands on the system drop to the point that the charging device is fully dispatched and can no longer maintain the SMC at $\eta_c\left(\alpha_{j(h)} - C_c^{\text{var}}\right)$. At this point the SMC begins to decline further, following the heavy line. However, the SMC I higher than it would have been without storage.

From hour **b** until hour **c** the charging device is fully dispatched and Equation 8b applies. During this interval, additional charging capacity would be valuable to the system since it would allow the storage to take in more energy at a lower price. Equation 8b computes the contribution to the marginal value of charging capacity in each hour. Just as in the case of other conversion technologies, $\gamma_{c,h}$ is the Lagrange multiplier on the constraint that the capacity of the charging device cannot be exceeded. Here $\gamma_{c,h}$ is the difference between $C_c^{\text{var}} + \lambda_h/\eta_c$, the cost of adding a unit of energy in that hour, and $\alpha_{j(h)}$, the marginal cost of adding to storage in that cycle. This is the value that additional charging capacity would provide in that hour. The marginal value of a unit of charging capacity is the sum of the γs over the year. For a single charging cycle, as illustrated in Figure 3, the contribution to the marginal value of charging capacity is the area of the grey semicircle bounded by $\alpha_{j(h)} - C_c^{\text{var}}$ at the top and λ_h/η_c at the bottom.

If the variable cost were zero and the charging were perfectly efficient, $\gamma_{c,h}$ would be equal to α_j - λ_h. In that case, the value of an additional unit of charging capacity, in that hour, would be just equal to the difference between the marginal cost of charging during that cycle and the SMC in that hour.

The storage can also charge during the discharging interval. This more easily described after discussing the system behavior while discharging.

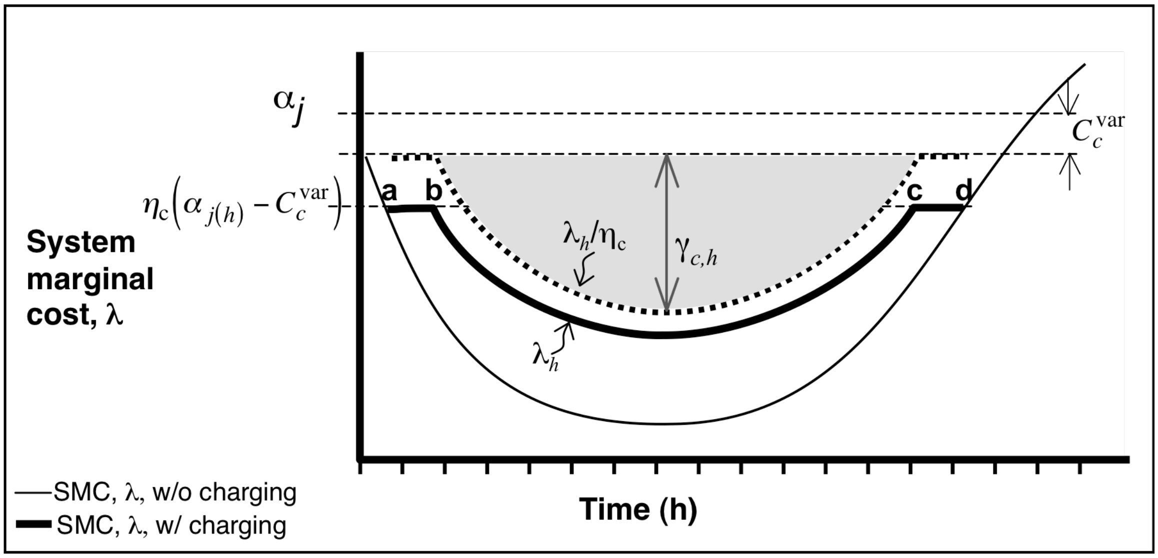

Figure 3: Illustration of changes in system marginal cost during a charging interval

Derivative wrt the rate of discharge: Dispatch and capital cost recovery of the discharge device, $g_{d,h}$:

This gives us the conditions for the optimal dispatch of the discharging device. Similar to the charging device there are four different system conditions that give us four different equations:

$$\frac{\partial L}{\partial g_{d,h}} = \begin{cases} \begin{matrix}\text{charging}\\ \text{interval}\end{matrix}, & j(h) \begin{cases} C_d^{\text{var}} - \lambda_h + \dfrac{\alpha_{j(h)}}{\eta_d} & h \notin H_d^* \\ C_d^{\text{var}} + \gamma_{d,h} - \lambda_h + \dfrac{\alpha_{j(h)}}{\eta_d} & h \in H_d^* \end{cases} \\ \begin{matrix}\text{discharging}\\ \text{interval}\end{matrix}, & j(h) \begin{cases} C_d^{\text{var}} - \lambda_h + \dfrac{\beta_{j(h)}}{\eta_d} & h \notin H_d^* \\ C_d^{\text{var}} + \gamma_{d,h} - \lambda_h + \dfrac{\beta_{j(h)}}{\eta_d} & h \in H_d^* \end{cases} \end{cases}$$

Setting these to zero and re-arranging gives the following equations governing the discharge of storage and the contributions to the marginal value of the discharge capacity:

$$
\left.\begin{array}{c}\text{discharging}\\ \text{interval}\end{array}\right., j(h)\begin{cases}\lambda_h = C_d^{\text{var}} + \dfrac{\beta_{j(h)}}{\eta_d} & h \notin H_d^* \quad \text{9a}\\[2ex] \gamma_{d,h} = \lambda_h - \left(C_d^{\text{var}} + \dfrac{\beta_{j(h)}}{\eta_d}\right) & h \in H_d^* \quad \text{9b}\end{cases}
$$

$$
\left.\begin{array}{c}\text{charging}\\ \text{interval}\end{array}\right., \quad j(h)\begin{cases}\lambda_h = C_d^{\text{var}} + \dfrac{\alpha_{j(h)}}{\eta_d} & h \notin H_d^* \quad \text{9c}\\[2ex] \gamma_{d,h} = \lambda_h - \left(C_d^{\text{var}} + \dfrac{\alpha_{j(h)}}{\eta_d}\right) & h \in H_d^* \quad \text{9d}\end{cases}
$$

The behavior of the discharge device is illustrated in Figure 4. This is analogous to the behavior of the charging device. During the discharge part of the cycle the storage begins to discharge once the SMC increases to $C_d^{\text{var}} + \beta_{j(h)}/\eta_d$. At this SMC, the earnings per unit discharged from the storage reservoir (i.e. not including the efficiency losses and operating cost the discharging device) is β_j.

Analogous to the charging cycle, between hours **a** and **b** the storage discharges at a rate to maintain the SMC at $C_d^{\text{var}} + \beta_{j(h)}/\eta_d$. After hour **b** the load on the system has risen to the point that the discharge device is dispatched to capacity and can no longer maintain that SMC. After time **b** the SMC rises following the heavy line.

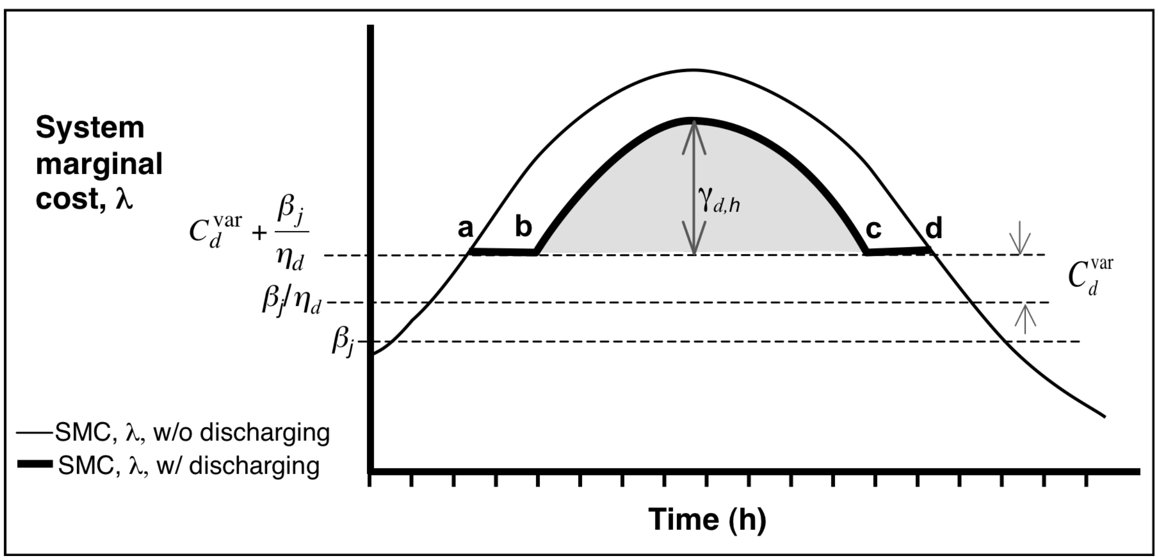

Figure 4: Illustration of system marginal cost during discharge interval

The contribution to the marginal value of discharging capacity, $\gamma_{d,h}$, is the difference between the SMC, λ, and $C_d^{\text{var}} + \beta_{j(h)}/\eta_d$. The area of the grey semicircle bounded by the SMC (with charging, the heavy line) on the top and the line $C_d^{var} + \beta_{j(h)} / \eta_d$ on the bottom is the contribution to the marginal value of discharge capacity for this cycle.

Derivative wrt the capacities of the generators, k_a: Capital cost recovery for generators and for the charge and discharge devices

This gives us the conditions for the optimal capacities of the generators

$$\frac{\partial L}{\partial k_a} = C_a^{cap} - \sum_{h \in H_a^*} \left(\gamma_{a,h} \bullet F_{a,h}^{prd} \right)$$

Setting to 0 and re-arranging yields

$$C_a^{cap} = \sum_{h \in H_a^*} \left(\gamma_{a,h} \bullet F_{a,h}^{prd} \right) \qquad 10$$

For the optimized system marginal value of capacity is equal to the marginal cost of capacity. The total marginal value of capacity is the sum of the marginal capacity values, γs, over the year. In the case of intermittent generators the available capacity in each hour is multiplied by $F_{a,h}^{prd}$ so the actual value provided by an increment of capacity is $\gamma_{a,h} \bullet F_{a,h}^{prd}$ in hour *h*.

This interpretation applies to the both the electric generators and to the storage charging and discharging devices.

Derivative wrt the capacity of the storage reservoir, k_r: Capital cost recovery of the storage reservoir

This derivative gives us the optimal conditions for the capacity of the storage reservoir

$$\frac{\partial L}{\partial k_r} = C_r^{cap} + \sum_j \alpha_j - \sum_j \beta_j$$

Rearranging and setting to 0 yields:

$$\sum_j \left(\beta_j - \alpha_j \right) = C_r^{cap} \qquad 11$$

From equation 11 we see that the marginal value of the reservoir is a function of the number of times that the reservoir fully cycles over the year and the differentials between α and β when it cycles. The marginal value of the storage reservoir is determined by the *minimum* price at which it discharges and the *maximum* price at which it charges.

Charging during the discharge interval and discharging during the charging interval

During the charging and discharging intervals of a cycle it is quite possible that the storage will be both charging and discharging during the interval. This would be particularly likely when the intervals extend over several days.

Equations 9c, and 9d show the conditions for discharging during the charging interval. If we discharge a unit of energy from storage, the value to the storage reservoir, after accounting for the losses and the operating cost of the discharge device, will be $\eta_d\left(\lambda_h - C_d^{\mathrm{var}}\right)$. It is worthwhile to discharge a unit of energy from the reservoir whenever this value is greater than $\alpha_{j(h)}$, the marginal cost of adding a unit of energy to the storage reservoir. Therefore, during the charging interval it will be worthwhile to discharge whenever;

$$\lambda_h \geq C_d^{\mathrm{var}} + \alpha_{j(h)} / \eta_d$$

Similarly, equations 8c and 8d show the conditions for charging during the discharging interval. The marginal value of discharging from the storage reservoir is $\beta_{j(h)}$. If the cost of adding a unit of energy is less than this, it is optimal to charge. The cost of adding a unit of energy is $\left(\lambda_h + C_c^{\mathrm{var}}\right)/\eta_c$. Thus it is worthwhile to charge whenever $\lambda_h \leq \eta_c\left(\beta_{j(h)} - C_c^{\mathrm{var}}\right)$.

Case when the same device charges and discharges

In this mathematical formulation charging and discharging are represented as separate devices. In most real storage technologies charging and discharging use the same physical device. When that is the case, the marginal value of capacity is simply the sum of the hourly marginal capacity values (γs) attributed to the device in either mode.

3. Practical illustration of the application and the marginal values of the storage system components

The following example uses the equations derived above to illustrate the marginal value and penetration of large-scale storage in a system based on data for California. It is not intended to be a model of the California system, but this gives a view of the results that could be obtained from the theoretical analysis derived above. The example computes the marginal values of charging/discharging capacity and reservoir capacity. Given the costs and efficiencies of these capacities for a given storage technology, we can determine the optimal capacities and penetration in the system.

3.1. Structure of the modeled system and the underlying data

This analysis is based on the hourly prices from a time dependent value study of the California system (PG&E, 2001) and loads for 2001. Figure 5 illustrates the pattern of prices over the year for this example. The peak load in this example has been scaled to 60 GW and the total generation over the year is 332,000 GWh. It assumes that the storage is

90% efficient on charging and discharging (81% efficient round trip). It also assumes that the charging and discharging uses the same device. The analysis does not make assumptions about the cost of the storage. The results of the analysis show how much storage would be optimal, given the costs of the capacities.

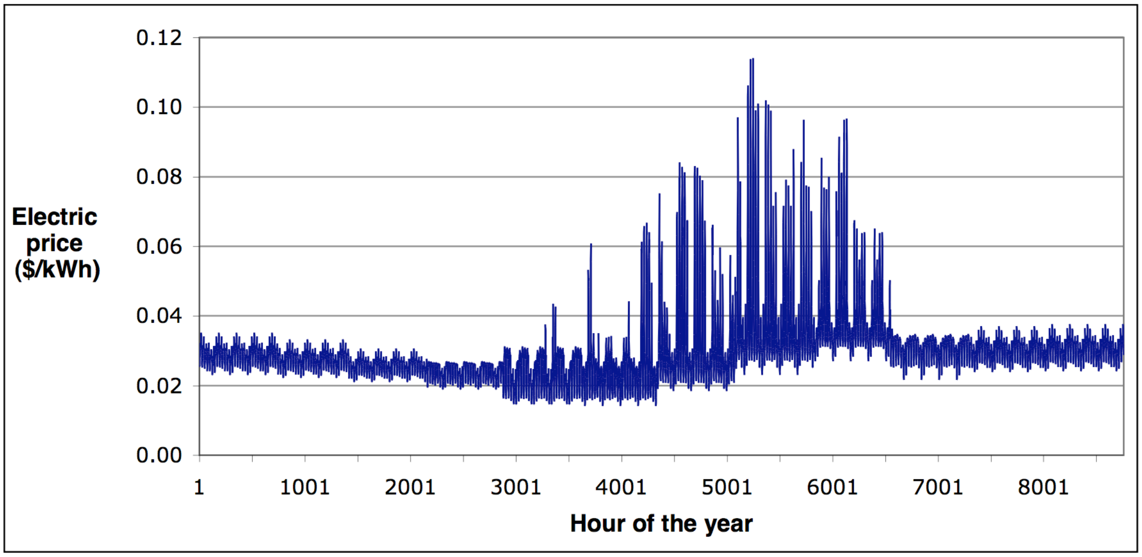

Figure 5: Patterns of prices over the year for this example

3.2. Modeling steps

The analysis first develops a relationship between load and price on the system. It then applies the equations above to determine the charging or discharging each hour of the year. This gives us the values of α and β for each cycle and the marginal values of capacity. The final step plots the contours of marginal values for storage reservoir capacity and charge/discharge capacity as a function of the reservoir and charge/discharge capacity.

The relationship between price and load is modeled using a bi-linear fit for each day. One linear fit is calibrated to the low load hours of the day and the other is calibrated for the highest hours of load each day. During most months the two linear fits are very similar. During the summer months there is a sharp break with rapidly rising prices once the load exceeds a threshold. The threshold is different for each day, so a different fit is needed for each day. Figure 6 illustrates the bi-linear fit for a summer day.

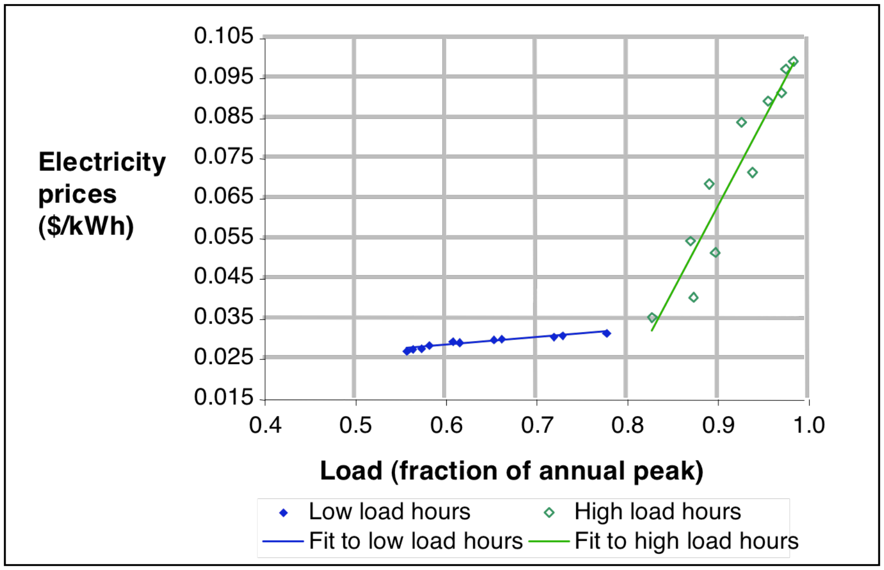

Figure 6: Example of bilinear fit on day 220

Figure 7 shows a scatter plot of the fitted prices and the original data. The bilinear fits do a good job of reproducing the price tracks over the year. However, since this is an illustration we have used the fitted data for the analysis, not the original data so that comparisons are internally consistent.

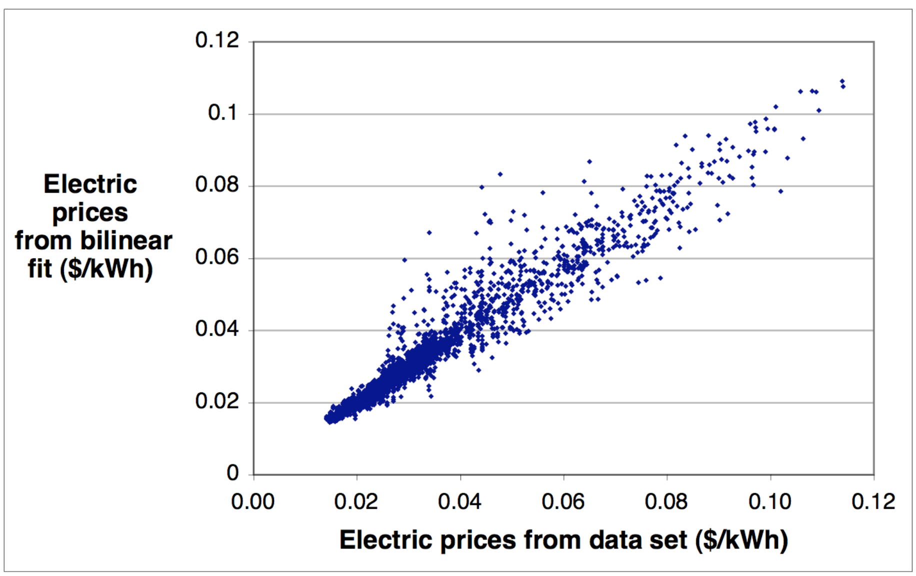

Figure 7: Scatter plot comparing system prices from original data and prices using bilinear fit and loads for each day

A series of cases was run assuming different values for storage energy capacity and charge/discharge power capacity in each case. For each case, the model was executed for each day over the year. The Solver function in Excel was used to determine if the storage can cycle in each day and to determine the optimal values of α and β. For each case the the αs, βs and γs were summed up over the year to give the marginal values of capacities for that case.

The hours in which the storage was required to completely charge and discharge (the values of f_j, and e_j in the theoretical formulation) were determined using a practical rule: The storage was completely cycled each day, if it was economically advantageous to do so. For each day values for α_j and β_j needed to fully charge and discharge were first determined. As long as the spread of SMC was great enough, α_j was less than β_j and it was economically worthwhile to cycle the storage fully. In some cases the SMC spread was so small that α_j would have to be greater than β_j in order to fully cycle the storage. This implies that if the storage were completely charged and discharged that day, the marginal cost of charging would be greater than the marginal revenue of discharging. Clearly this would not be efficient. In those cases the storage was only cycled up to the point that α_j was equal to β_j. During these partial cycles the storage system does earn net revenues. But these revenues do not increase the marginal value of storage capacity since the storage system could have earned the same revenue with less capacity. The appendix describes the execution in more detail, and illustrates the cases when the storage can fully charge and discharge over a day, partially charge and discharge, and cannot charge at all.

3.3. Results from the analysis

The primary result from the analysis are shown in Figure 8 which shows two super-imposed sets of contours, one set for the marginal values of reservoir capacity and the other set for the marginal values of charge/discharge capacity. These are plotted as functions of the reservoir energy capacity and charge/discharge power capacity.

For a given type of storage technology, the marginal costs of reservoir and charge/discharge capacities are known. We will assume they are constant (this excludes pumped storage) We can determine the contour that corresponds to each marginal cost. At the point where the two contours intersect the marginal values of reservoir capacity and of charge/discharge capacity will be just equal to their marginal costs. This gives the optimal capacities for that storage technology in this example system. To illustrate, assume (optimistically) that there is a storage technology with an annual cost 2.0 $/kW-yr for the charge/discharge capacity and a reservoir cost of cost of 1.5 $/kWh-yr. The optimal storage system for this example would have a charge/discharge capacity of 1.25 GW and a reservoir capacity of about 6.3 GWh. If the annual cost of the reservoir were to decline to 1.0 $/kWh-yr, the optimal capacities would be 2.2 GW of charge/discharge capacity and 12.5 GWh of reservoir capacity.

As would be expected, both types of capacity show decreasing returns to scale. At very small charge/discharge power capacity the marginal value of capacity is 14$/kW-yr. However, as the charge/discharge capacity increases, the marginal value drops essentially to zero, 0.01 $/kW-yr. Similarly, at a small volume of energy storage capacity the marginal value of storage capacity is 2.5 $/kWh-yr. At larger capacities the marginal value drops to 0.05 $/kWh-yr, in this example.

Increasing the capacity of one component improves the marginal value of the other component. At very small capacities this effect is very strong. As a result the two sets of contours are fairly parallel for small values of reservoir and charge/discharge capacity. If storage is economically feasible at all, several GWhs of storage would be feasible. However, at levels above a few GWhs of storage, the contours begin to diverge.

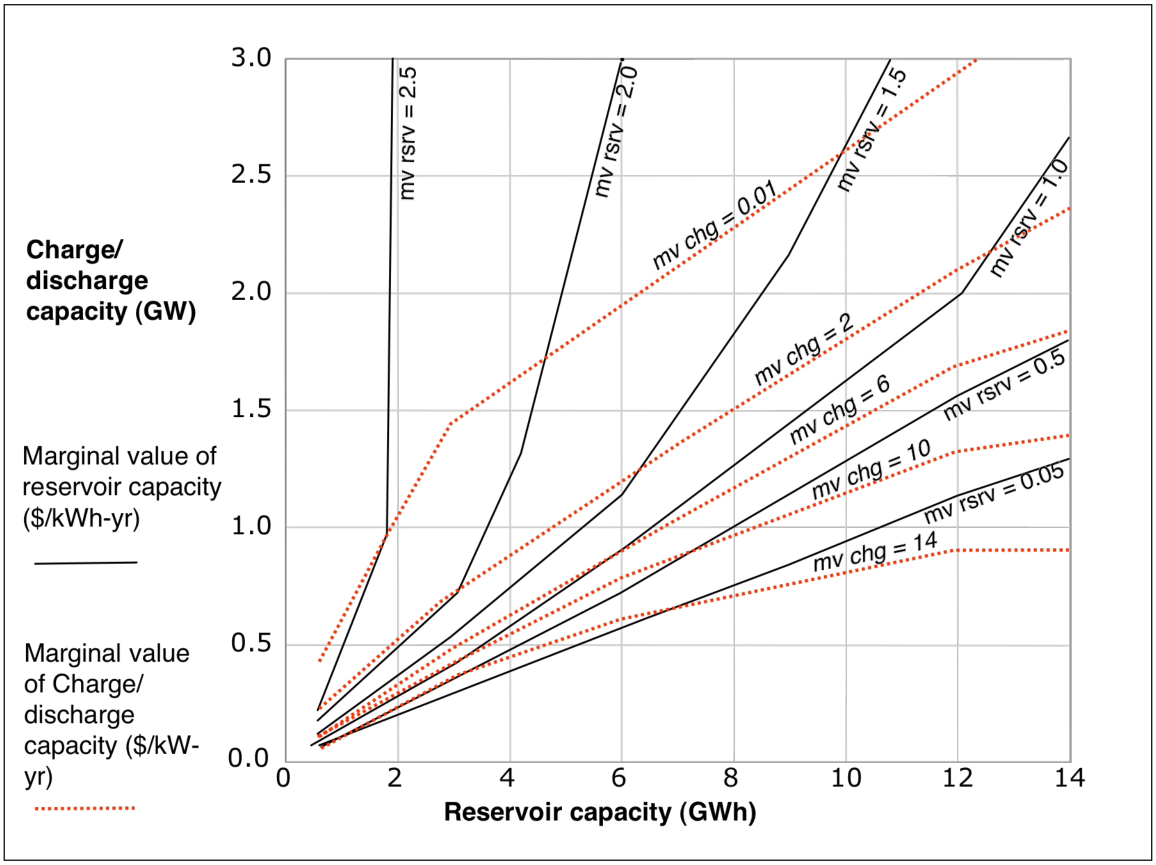

Figure 8: Contours of the marginal values of storage reservoir capacity and charge/discharge capacity

This example finds a low value of reservoir capacity. The maximum value plotted in the figure is 2.5 $/kWh-yr for a reservoir capacity of a few hundred kWh. The marginal value of reservoir capacity increases as the capacity decreases. However, it is bounded. An upper bound on the marginal value of reservoir capacity that is cycled daily is the sum of the daily differences between the maximum and minimum prices. This is essentially the value of a very small storage reservoir--a few kWh of storage and a large charging capacity that would allow it to charge and discharge in one hour, with perfect efficiency. Such a small storage could charge completely every day and not disturb the system prices. For such a small system the upper bound value is 5.75 $/kWh-yr for this set of prices. When the model is run with a very small capacity and perfect efficiency, the value of storage capacity reaches 5.35 $/kWh-yr. However, because the charge/discharge capacity is so large compared to the reservoir capacity, the marginal value of charging capacity is only 0.0027 $/kW-yr.

The low value of storage capacity is partly due to the small daily price variations during winter and spring for this data set. However, the low value is also due to the fact that during the summer, the price during the highest price hours is sensitive to the load on the system (see Figure 6). As soon as storage becomes large enough to affect the system, the storage discharge lowers the peak prices. The effect of this can be seen in the price duration curves shown in Figure 9. In this example, peak prices are lowered more than off peak prices are increased. Further work will be needed to determine if this is a general result.

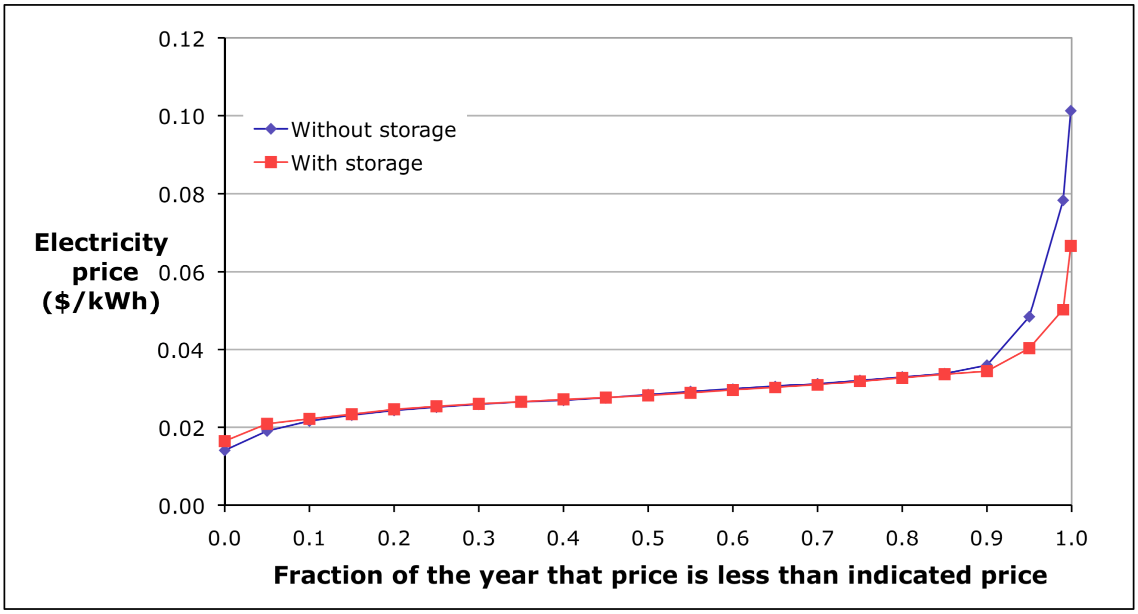

Figure 9: Price duration curves without storage and with 30 GWh of reservoir storage and 10 GW of charge/discharge capacity

These results are based on data from one region for a single year. We can expect that different regions and different years will result in different values. Graves, et al (1999) studied systems with small discharge capacity (1 MW) and large reservoir capacity (20 MWh). They found a wide variation in the value of storage ranging from 10 to 13 $/kW-yr at the California Oregon border to 26 to 32$/kW-yr at Palo Verde. They also found substantial year-to-year differences in value, in some cases up to 50% variation. To evaluate storage in any given location, it will be necessary to consider its performance over a series of years to better estimate its value over its lifetime.

4. Future work

This study provides the basic economic framework for evaluating the economics of energy storage and illustrates the application to an existing system. However, the economics of storage itself is only part of the question. The longer-term goal of this research is an understanding the role that storage might play in future system. We can identify several areas where future study is needed:

- Investigate the long-term impact of large-scale storage on the structure of the system. Large-scale storage changes the patterns of prices on the system. These changes will change the optimal mixes of the dispatchable and intermittent generators. Storage can increase intermittent penetration if it raises prices during hours that the intermittent generates—thereby increasing the revenue to the intermittent. Conversely, storage could discourage some types of intermittent penetration (e.g. solar) if it lowers the prices during hours that the intermittent generates.
- Find practical procedures for optimizing the operations of real systems. Operators need to specify the future hours in which the storage should optimally be full charged and discharged. They then need to estimate the values of α and β to determine the prices at which they should charge and discharge in order to fully cycle the storage by the specified hours. We need to determine strategies for doing this, and estimate the performance of storage under realistic conditions.
- Determine the most important R&D efforts for improving storage. The analysis shows the impacts of changing marginal costs and efficiencies of different storage components. Further studies should demonstrate the way that improvements in each dimension could affect the marginal values of storage for different applications in different regions.

5. Conclusions

If storage is to be a significant part of future energy systems it will be deployed at scales large enough to affect the prices on the system. The change in prices affects both the ultimate penetration of storage and the economic penetration of other technologies. This work provides the theoretical framework to determine the optimal operation of storage, evaluate its effect on system marginal prices, and assess the marginal value of the storage components. Applying this theory to the operation of a real energy system shows us the changes in prices that might occur, and the interaction between charge/discharge capacity and the storage reservoir capacity. The capacity of each component affects the marginal value of the other, so they must be optimized together. This affect is particularly strong at low levels of penetration. Finally, substantial future work needs to be done to better understand the impacts of storage on the balance of the system, and to understand how storage can be optimally operated in realistic settings.

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8. Appendix: Detailed description of marginal costs and storage operation

For each charge and discharge cycle the rates of charging and discharging are controlled by the values of α_j and β_j. These values are set so that the storage is fully charged by hour f_j and then fully discharges by hour e_{j+1}. Increasing α increases the amount stored. Decreasing β increases the amount discharged. To balance the charging and the discharging, levels of α and β must be found such that: a) the charging and discharging are equal, and b) the reservoir capacity is not exceeded.

The model first attempts to cycle the storage each day. However, in many days fully charging and discharging the storage would require that α_j be greater than β_j. When this happens, it implies that the marginal cost of charging is greater than the marginal revenue from discharging. This is not optimal for the operation of storage. When this case arises, α_j and β_j are set equal to each other and adjusted so that the total charge into the storage reservoir is just equal to the total discharge from the reservoir (note that because of efficiency losses, the total energy taken from the system is greater than the energy returned to the system).

The storage charges when the SMC is less than $\eta_c\left(\alpha_{j(h)} - C_c^{\text{var}}\right)$. It discharges when the SMC is greater than $C_d^{\text{var}} + \beta_{j(h)}/\eta_d$. To simplify notation in this discussion let

$$\alpha^*_{j(h)} = \eta_c\left(\alpha_{j(h)} - C_c^{\text{var}}\right), \text{ and}$$

$$\beta^*_{j(h)} = C_d^{\text{var}} + \beta_{j(h)}/\eta_d$$

The difference between β and α is the contribution in that cycle to the marginal value of reservoir capacity. The contributions are added up over the year to arrive at the total marginal value of reservoir capacity over the year.

Three cases are illustrated in the following figures. In these cases the storage capacity is 24 GWh and the charging capacity is 3 GW:

- The reservoir can completely charge and discharge during the cycle (Figure 10). In this case α is less than β so there is a net revenue and a contribution to the marginal value of storage capacity since the storage would have earned more on this cycle if there had been more capacity. Also note that the SMC is less than α^* during charging and greater than β^* during discharging. This implies that there is a contribution to the marginal value of charging and discharging capacity.

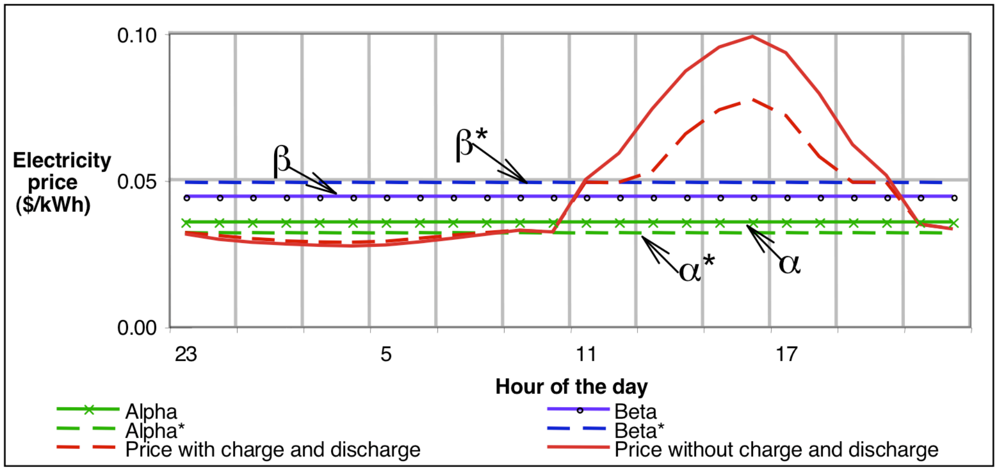

Figure 10: Marginal system costs and alpha and beta in cases for day 220, storage can completely charge

- The reservoir can partially charge (Figure 11). Here the storage cannot economically completely charge and discharge even when α equals β. Because α equals β there is no contribution to the marginal value of storage capacity for this cycle. However, there is still a net revenue to the storage. There is no contribution to the marginal value of storage capacity because the storage would have earned just as much with less capacity. During the charging interval the SMC is less than α* so there is a contribution to the marginal value of charging capacity. However, during the discharging interval the SMC is equal to β* so there is no contribution to discharge capacity.

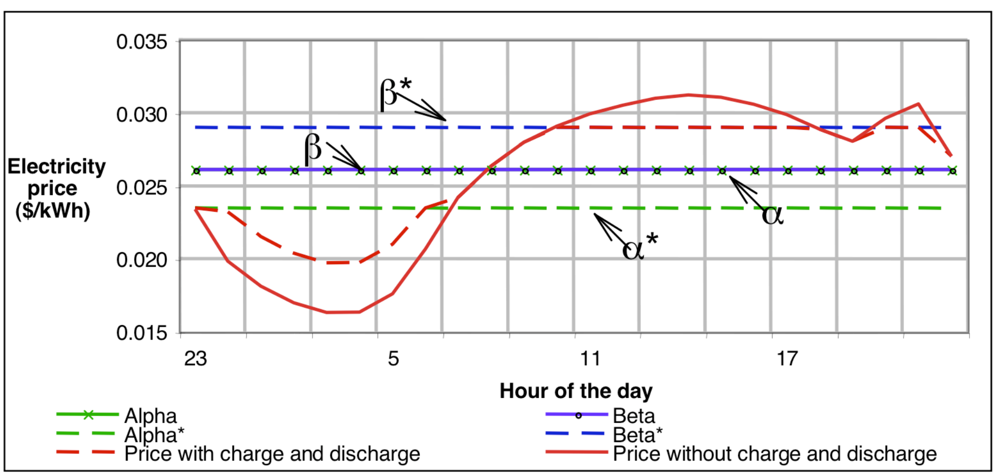

Figure 11: Marginal system costs and alpha and beta in cases for day 121, storage can only partially charge

- The reservoir cannot economically charge at all (Figure 12). Even if α equals β the charging and discharging prices are still outside of the range of prices for that day

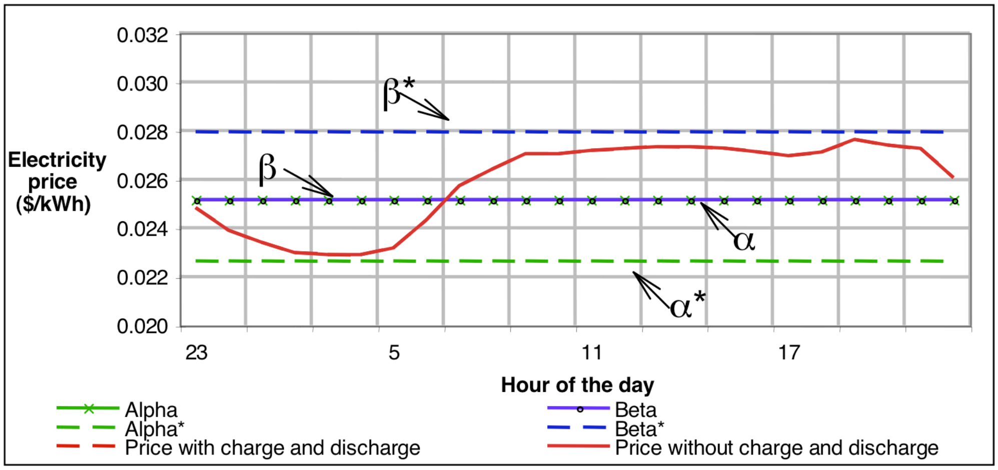

Figure 12: Marginal system costs and alpha and beta in cases for day 80, storage cannot economically charge